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Investigating Steady-State Operating Scenarios on DIII-D Using Flexible Current Drive Actuators

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I. Introduction

Fully noninductive operation ($f_{NI}=I_{NI}/I_p=1$) is planned for many next-step tokamaks, including ITER, FNSF-AT [1], and DEMO. A possible scenario for achieving high fusion gain, high bootstrap current fraction ($f_{BS}=I_{BS}/I_p$) operation is to use an elevated minimum safety factor (q_{min}) and high normalized β_{tor} (β_N), since $f_{BS} \propto \beta_{pol} \propto q\beta_N$ and fusion power $\propto \beta_N^2$. On DIII-D, neutral beam injection (NBI) and electron cyclotron (EC) waves are used for heating and current drive. NBI is the primary tool for attaining high β_N on DIII-D but high power on-axis NB current drive (NBCD) tends to drive peaked current density profiles and low q_{min} . Therefore one of the four beamlines was upgraded to provide a flexible injection angle between 0° and 16.5° to horizontal (Fig. 1). When the magnetic field pitch is aligned with the beam injected at 16.5° , significant off-axis current drive was predicted and confirmed to exist [2]. This current density is distributed widely about the plasma half-radius.

Compared to on-axis heating, off-axis heating reduces the on-axis pressure and current density, effectively broadening both profiles which is known to increase the β_N limit due to ideal-wall kink modes [3]. Off-axis NBI was used in steady state experiments that had two goals. The first was to demonstrate $q_{min}>2$ and $\beta_N>4$ plasmas with broad current and pressure profiles – conditions expected in a steady state DEMO. Broad profiles are expected to have high β_N limits due to increased wall

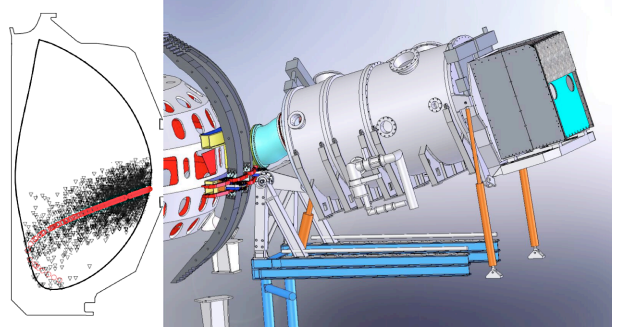


Figure 1. 5 MW of off-axis neutral beam injection 16.5° to horizontal on DIII-D.

stabilization, and good confinement due to a large volume of weak or negative magnetic shear [4]. The second goal was to extend high performance elevated q_{\min} operation to multiple current profile relaxation time scales (τ_R) to confirm passive stability of tearing modes and provide a demonstration of conditions that could be useful for ITER and FNSF.

II. Exploration of Access to $q_{\min} > 2$, High β_N Operation

Broader current and pressure profiles have been achieved using off-axis NBI compared to on-axis NBI. Previous experiments using only on-axis NBI and ~ 2.25 MW of off-axis electron cyclotron current drive (ECCD) showed that it is difficult to sustain q_{\min} above 2 at $\beta_N \approx 2.7$, $B_T = 2.1$ T, and $q_{95} = 6.7$. These conditions were reproduced with the following changes: (1) up to 4 MW off-axis NBI, (2) an additional ~ 1 MW of EC power, and (3) reversed toroidal field polarity to maximize off-axis NBCD. Figure 2 compares key equilibrium quantities obtained with and without off-axis NBI. The plasma heated by off-axis NBI was sustained with $q_{\min} \approx 2.4$ and $\rho_{q_{\min}} \approx 0.3$ at $\beta_N \approx 2.7$ for as long as NBI energy was available. The pressure profile peaking factor was reduced from ~ 3.5 down to ~ 2.5 . The pressure profile broadening is due chiefly to a less peaked fast ion pressure profile and increased electron heating at mid-radius by the off-axis NBI and ECCD, and to a lesser extent by reduced divertor pumping.

Plasmas produced with the highest values of q_{\min} (2-3) typically had a thermal energy confinement time (computed using the measured thermal profiles) that matched or exceeded the ITER98y2 thermal confinement scaling prediction [5]. However the same plasmas had a $\sim 18\%$ lower global energy confinement scale factor H_{89P} (thermal+fast ion, [6]) than plasmas with q_{\min} between 1 and 1.5. This suggests enhanced fast ion loss at higher q_{\min} and qualitative evidence for this is seen by increased Alfvén eigenmode activity with increasing q_{\min} . While the $q_{\min} > 2$ plasmas have calculated ideal-wall $n=1$ β_N limits in excess of 4, with the available heating power the maximum β_N achieved with $q_{\min} > 2$ was ~ 3.3 . Ongoing work is

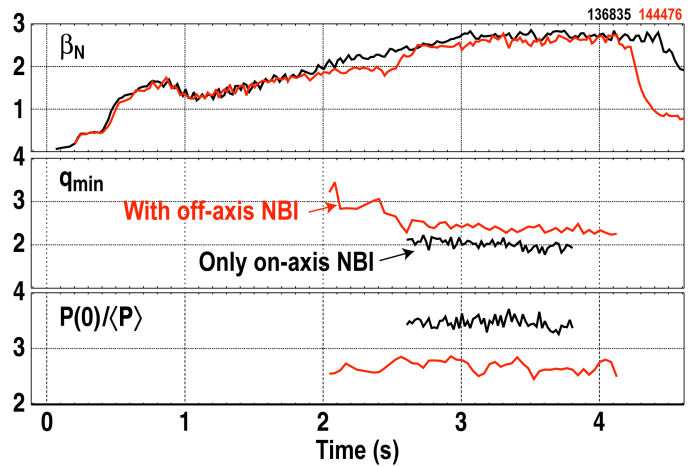


Fig. 2. Using off-axis NBI improves access to and sustenance of broad current and pressure profiles with $q_{\min} > 2$.

focusing on new fast ion and turbulence measurements for a more detailed understanding of the relatively poor fast ion confinement in these plasmas to determine if the dominant transport mechanisms can be mitigated.

III. Extension of High Performance, Quasi-Stationary Operation to $2\tau_R$

Off-axis NBI has proved beneficial for achieving discharges with modest q_{min} (1.3-1.8) to optimize profiles for stability and sustain them for a suitable duration. Such plasmas have been shown [7] on DIII-D to be promising candidates for long pulse or fully noninductive operation on an ITER-sized machine with projected fusion gain $Q \approx 5$. The $m/n=2/1$ tearing mode is the most common instability that can terminate good performance, and this is sensitive to the current profile and the proximity to the ideal-wall $n=1$ kink mode β_N limit [8]. The demonstrations of nearly or fully noninductive operation on DIII-D have been limited to durations less than $1\tau_R$ and β_N close to predicted ideal MHD limits [9]. When operating close to stability limits one must evaluate the evolution of the current profile to a stationary state over several τ_R to demonstrate access to and robustness of the target equilibrium. Better still is to adjust the plasma parameters to raise the stability limit far above the required operating pressure.

Using off-axis NBI, quasi-stationary plasmas have been produced without tearing modes for $2\tau_R$ with $q_{min}=1.4$, $\beta_N=3.5$, 50% bootstrap current, 70-75% noninductive current, and an equivalent fusion gain that projects to $Q \approx 5$ in an ITER-sized device. The duration is limited by the NBI energy. This surpasses earlier results in similar plasmas lacking off-axis NBI and with less ECCD power that were stationary for $1\tau_R$ (Fig. 3, black traces).

The loop voltage profile is nonzero but relatively uniform by the end of the high β_N phase (Fig. 4),

and q_{min} does not evolve to 1 in experiment or simulation [10] (Fig. 5). Ideal stability analysis using the DCON code [11] predicts the no-wall $n=1$ kink mode β_N limit is in the range of 3-3.4, while the ideal-wall $n=1$ β_N limit is 4-5. (Fig. 6). Compared to similar plasmas without off-axis NBI, the pressure profile is less peaked, and this contributes to the high calculated β_N limits. Replacing the remaining inductive current density in these plasmas will require more

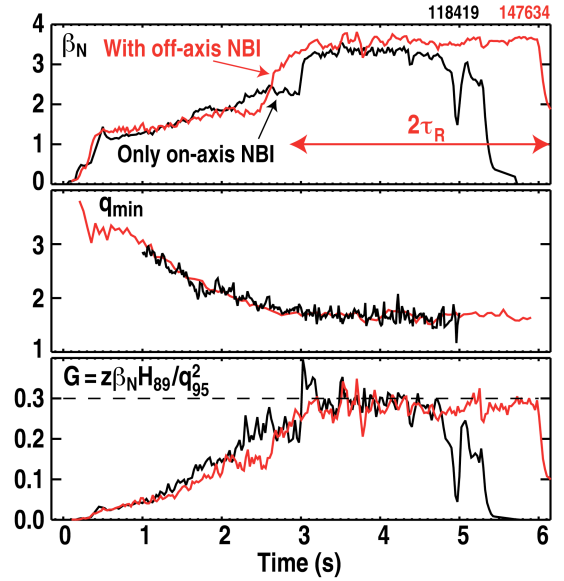


Fig. 3. High performance quasi-stationary plasma duration extended by using off-axis current drive.

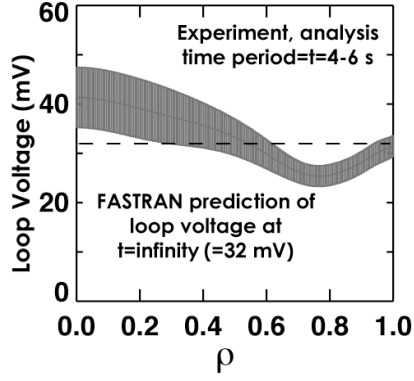


Fig. 4. At the end of the high β_N phase the loop voltage is approaching the fully relaxed value predicted by FASTRAN [12].

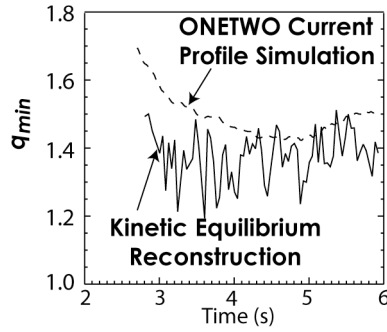


Fig. 5. With a nearly relaxed loop voltage and $\sim 70\%$ noninductive fraction q_{min} stays near 1.4.

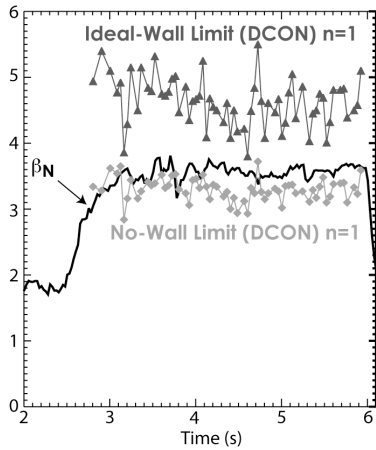


Fig. 6. Calculated ideal $n=1$ kink β_N limits.

current drive power and operation close to the predicted ideal wall β_N limit for higher bootstrap fraction.

IV. Summary

On DIII-D, progress has been made in elevated q_{min} steady state scenario development by using off-axis NBI. Current and pressure profile broadening enables access to higher ideal MHD β_N limits. Plasmas with $q_{min} > 2$ so far have lower normalized energy confinement H_{89P} than similar plasmas with lower q_{min} . Plasmas with $q_{min} \approx 1.4$ have been taken to nearly stationary conditions for $2\tau_R$ at $\beta_N = 3.5$. This work was supported by the US Department of Energy under DE-AC52-07NA27344, DE-FC02-04ER54698, DE-AC05-00OR22725, DE-FG02-04ER54761, DE-AC02-09CH11466, and DE-FG02-06ER84442.

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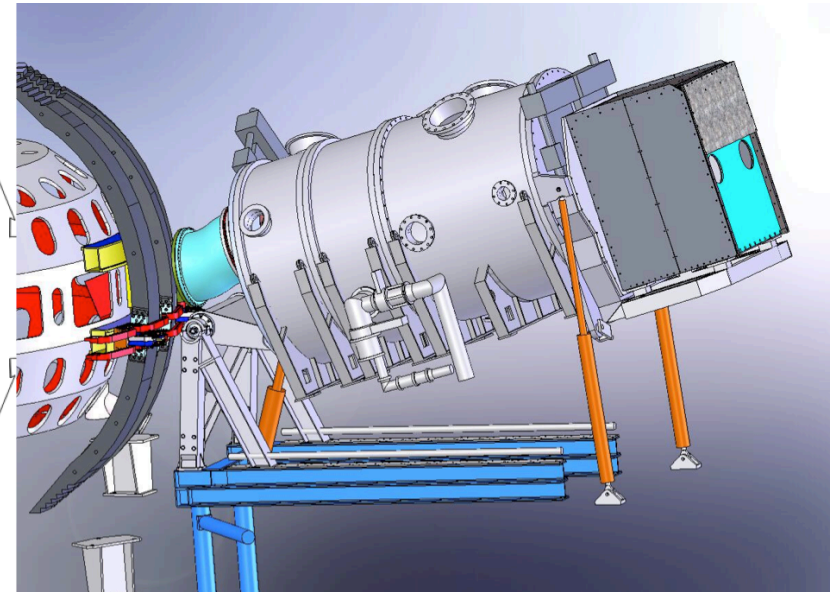
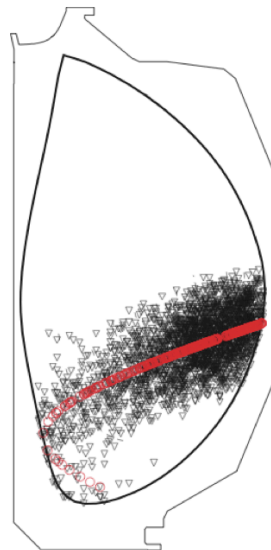
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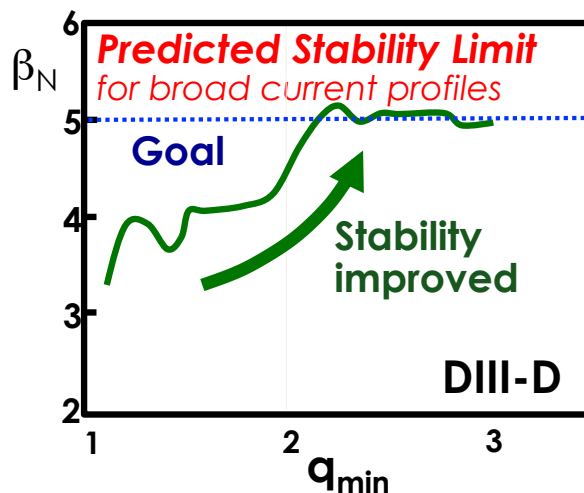


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Steady State Operation Needs Motivate Broad Current Profiles & High q_{\min}

Need High
Bootstrap Current
Fraction $\propto q\beta_N$

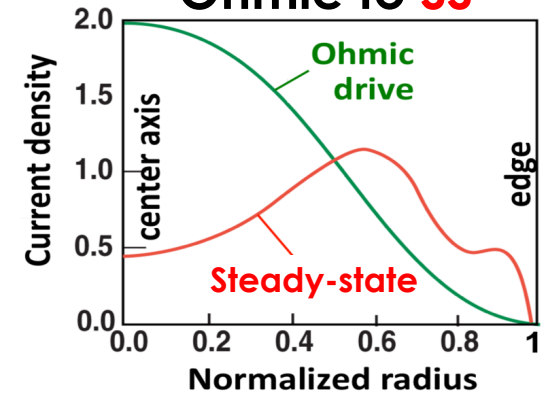
Need High β_N Stability:



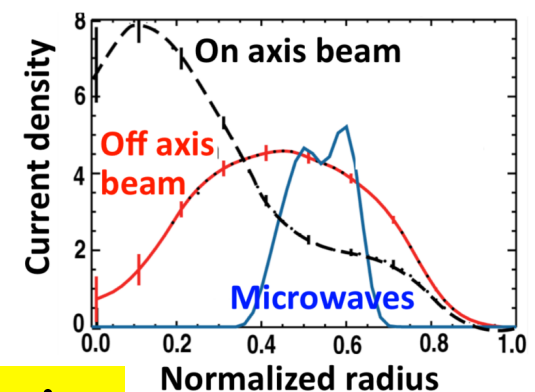
Need High Fusion
Gain $\propto \beta_N H / q_{95}^2$,
So Low q_{95}

**Broad, Off-Axis
Current Density &
High q_{\min}**

**Goal: Move from
Ohmic to **SS****



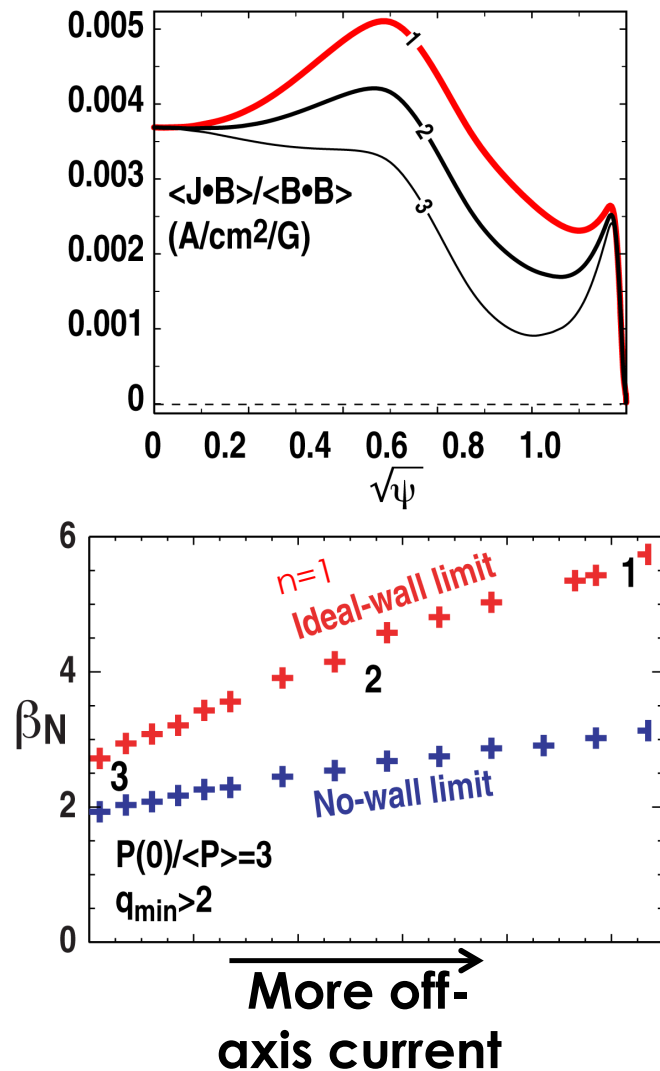
**Flexible, Matched
DIII-D Tools**



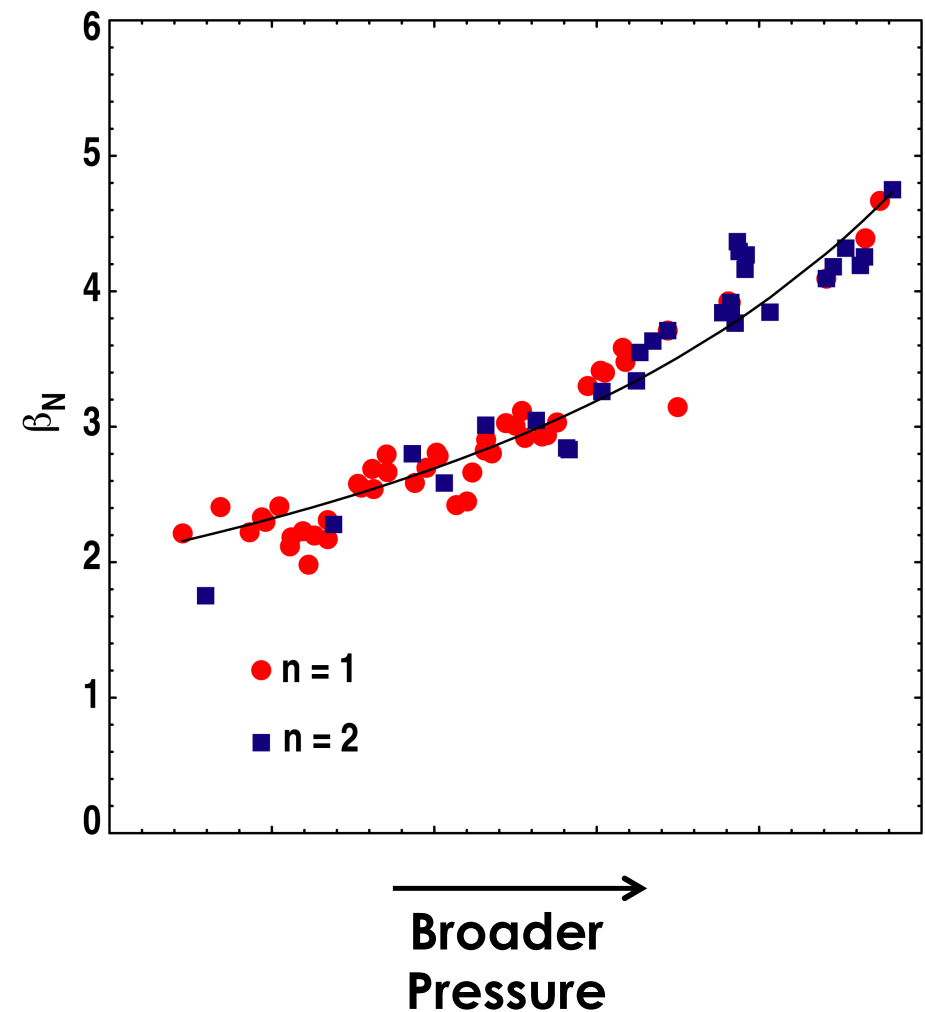
**DIII-D is Developing the Physics Basis
of Steady State Operation**

Modeling Shows Both Broad Current and Broad Pressure Profiles Are Important for Raising the Ideal-Wall β_N Limit

Corsica/DCON Modeling: 2 Separate Studies

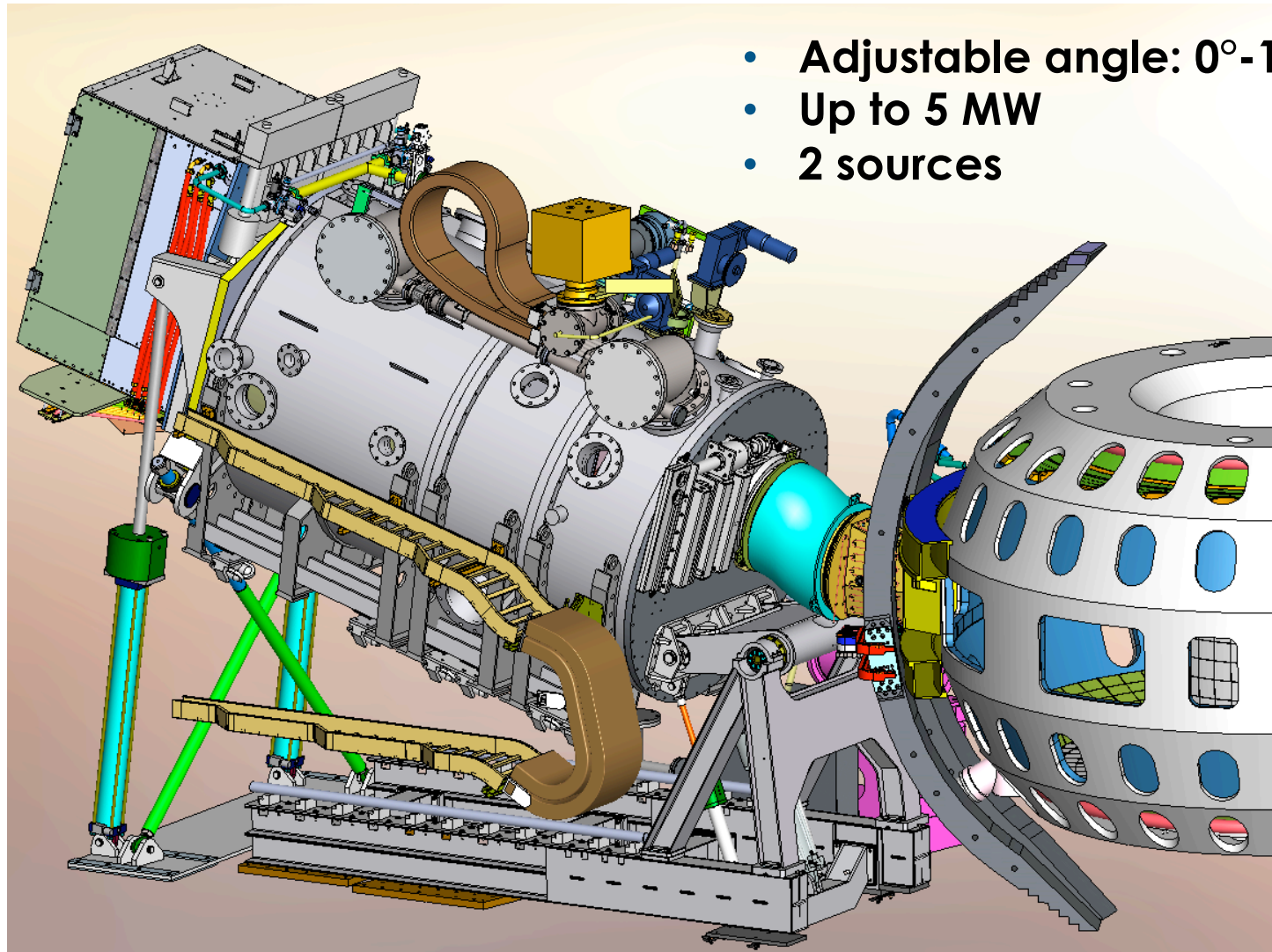


(fixed $p(\rho)$)



(fixed $q(\rho)$)

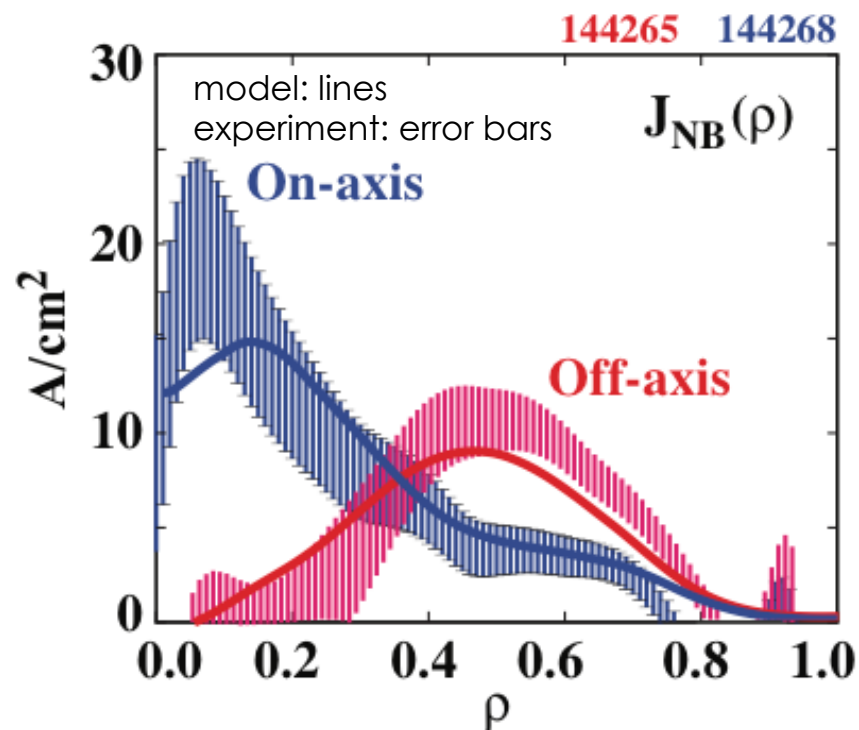
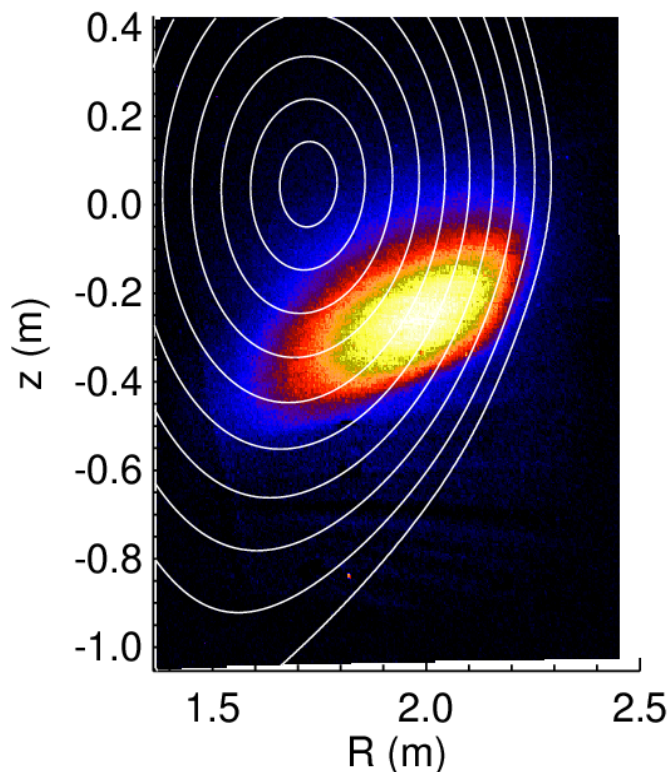
In 2010-2011, One Beamline Was Modified to Allow Off-Axis Injection



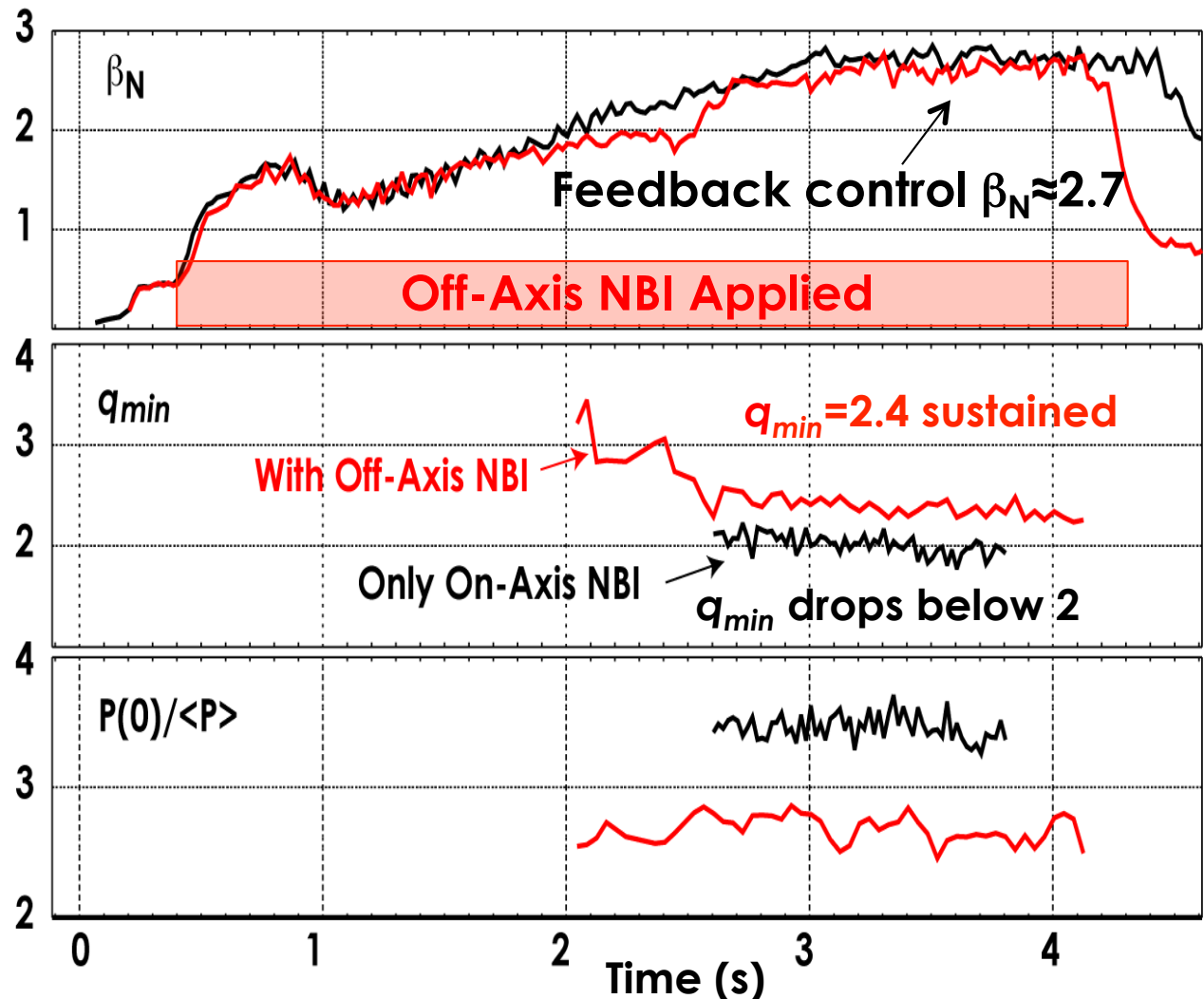
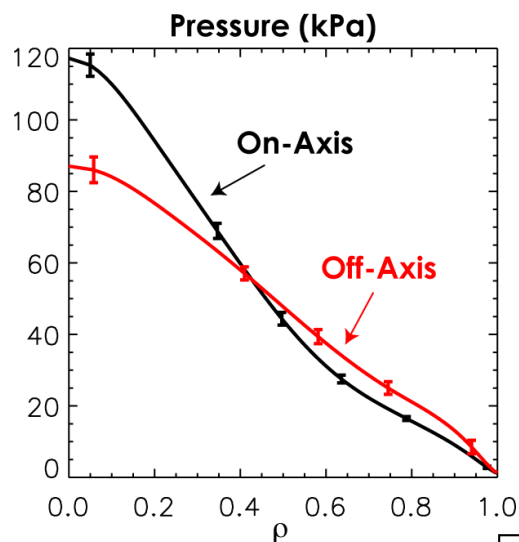
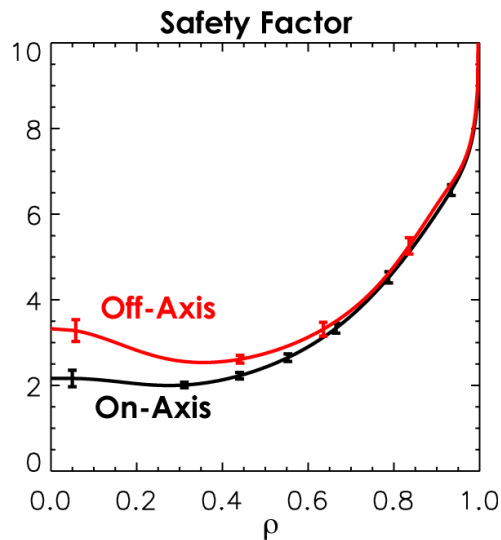
Measurements of NBCD in MHD-Free *H*-modes Agree With Classical Model Predictions

D α imaging of off-axis beams confirmed geometry & power for inclusion in NUBEAM model

- $\beta_N < 2.3$, monotonic q , $q_0 \sim 1.1$
- Measure $J_{NBI} = J_{tot} - J_{BS} - \sigma_{neo} d\psi/dt$
- No obvious anomaly related to microturbulence
- See poster, EX/P2-13



$q_{min} > 2$ Sustained With Broader Pressure Profile Using Off-Axis NBI and Additional ECCD Power

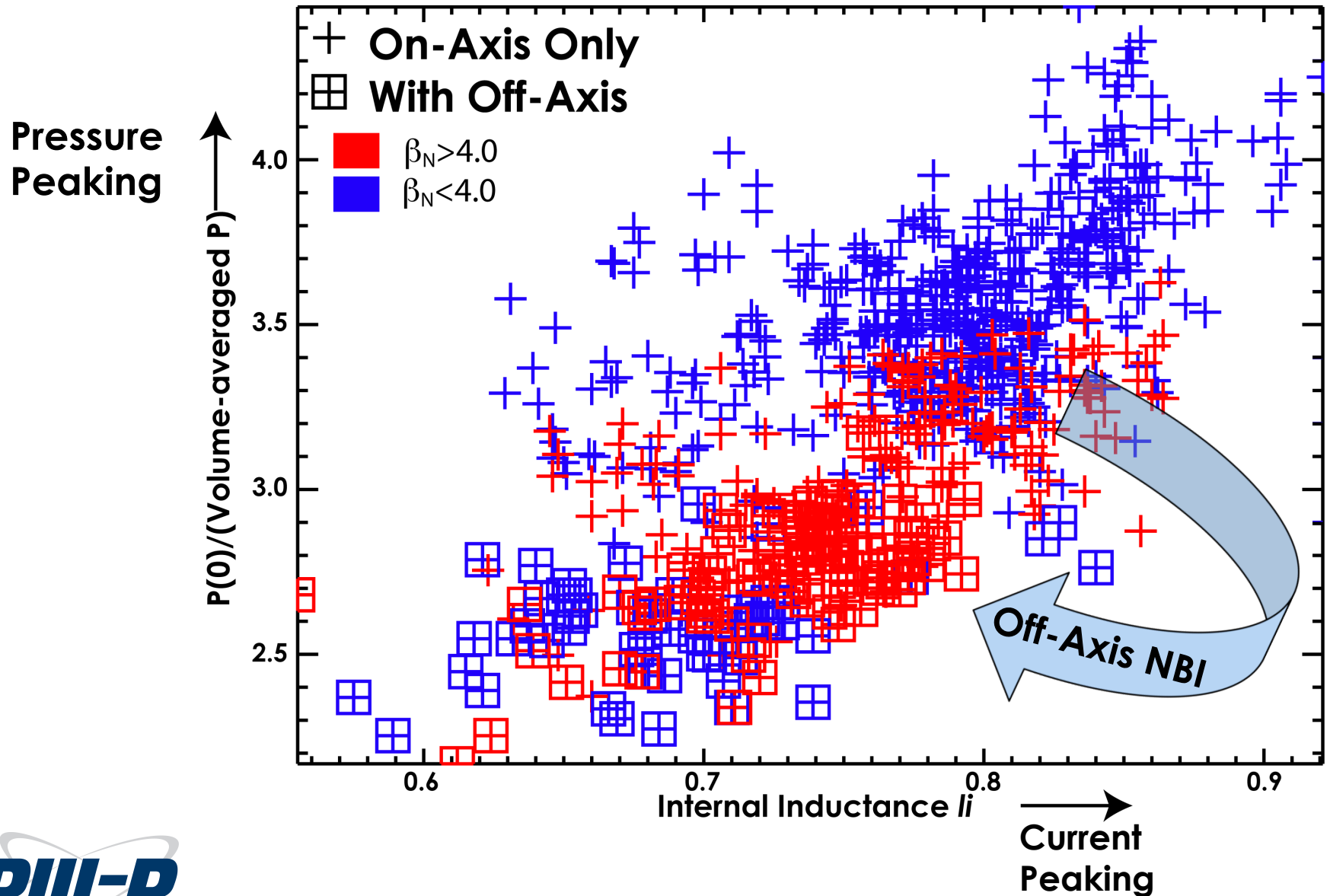


Shots 136835, 144476

Max $\beta_N = 3.3-3.5$ achieved with
 $q_{min} > 2$ limited by available power

Ideal MHD Stability Analysis of Experimental Equilibria Shows Accessing Broader Profiles Raised the β_N Limit

Ideal-wall $n=1$ β_N limits calculated by DCON

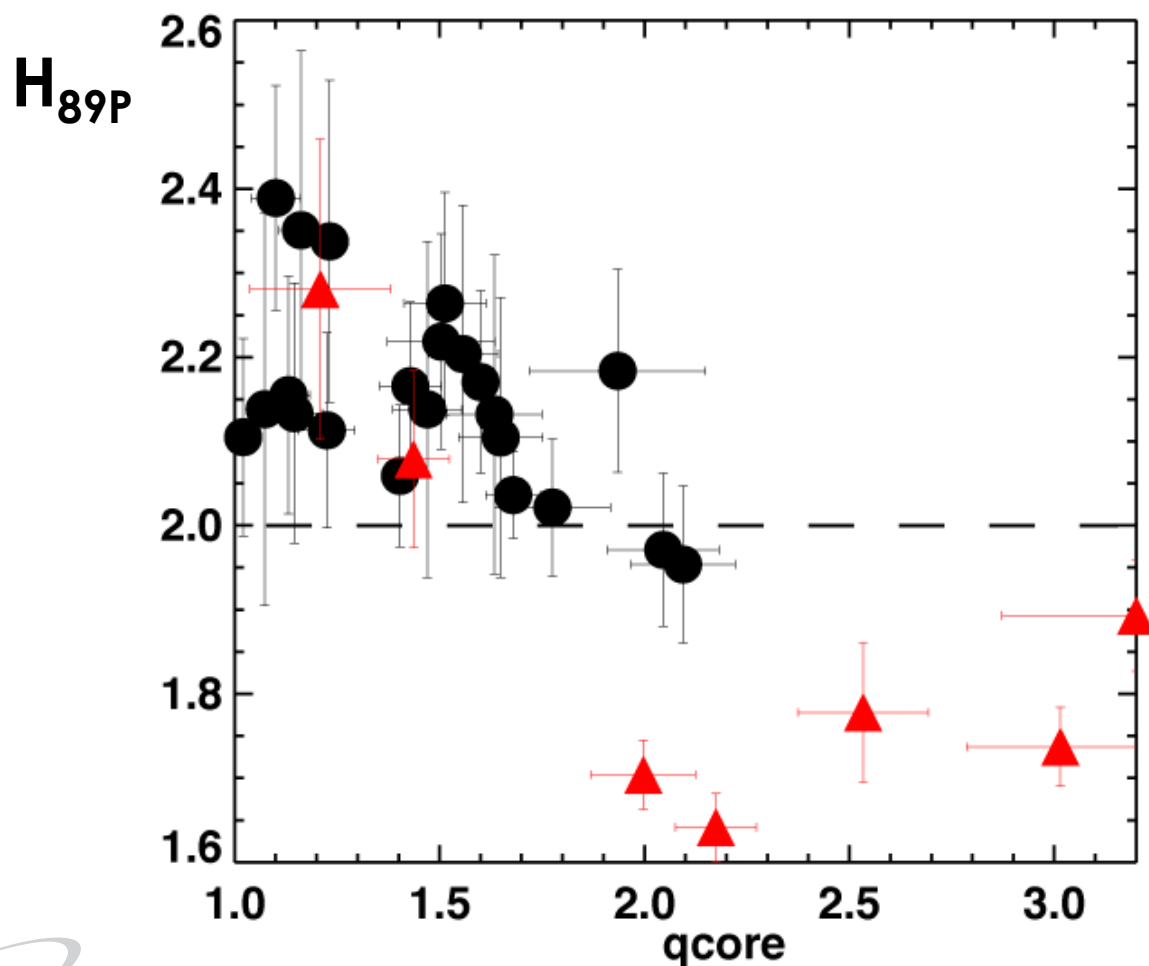


Highest q_{min} Plasmas Have $H_{89} < 2$: Less Than Typical H -Mode Global Confinement

● No off-axis beams used

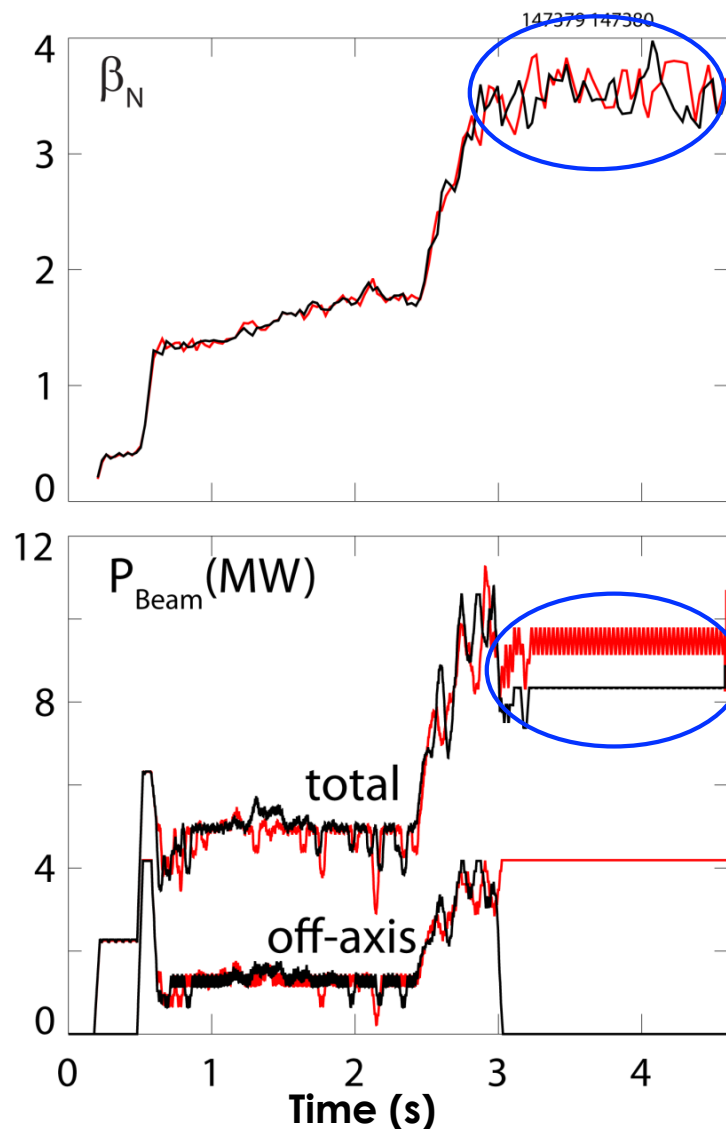
▲ Off-axis beams used

“ q_{core} ” is average of q from $\rho = 0-0.3$



H_{89} includes
thermal + fast
ion energy

Off-Axis Injection Itself Results in Only a Small Reduction in Confinement Time

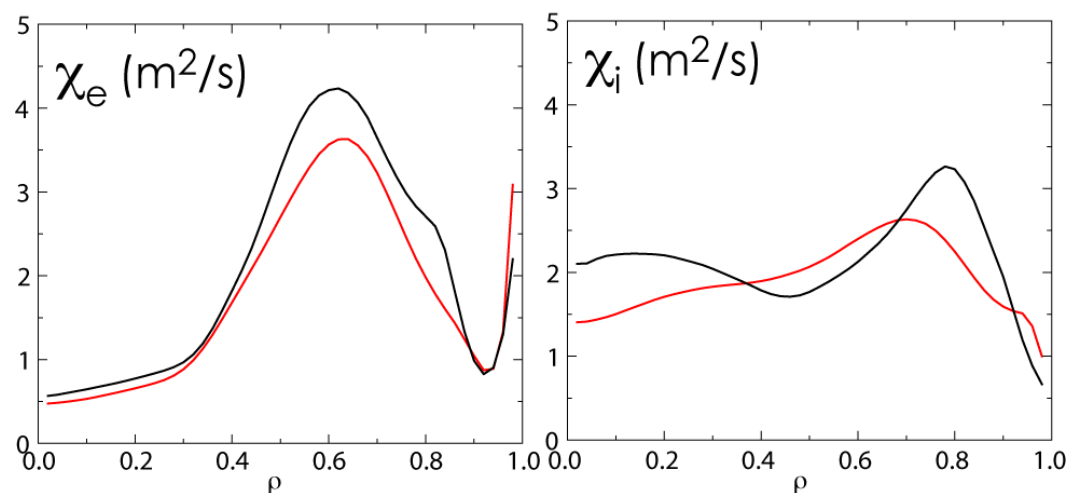


- 2 discharges compared at equal β_N

- Both with $q_{\min} \approx 1.1$

- Discharge with all on-axis injection requires 10% less total power

- Off-axis injection reduced τ_E by 10%
- H_{89} (≈ 2.3) reduced by 5%
- Puts power at radius with higher χ

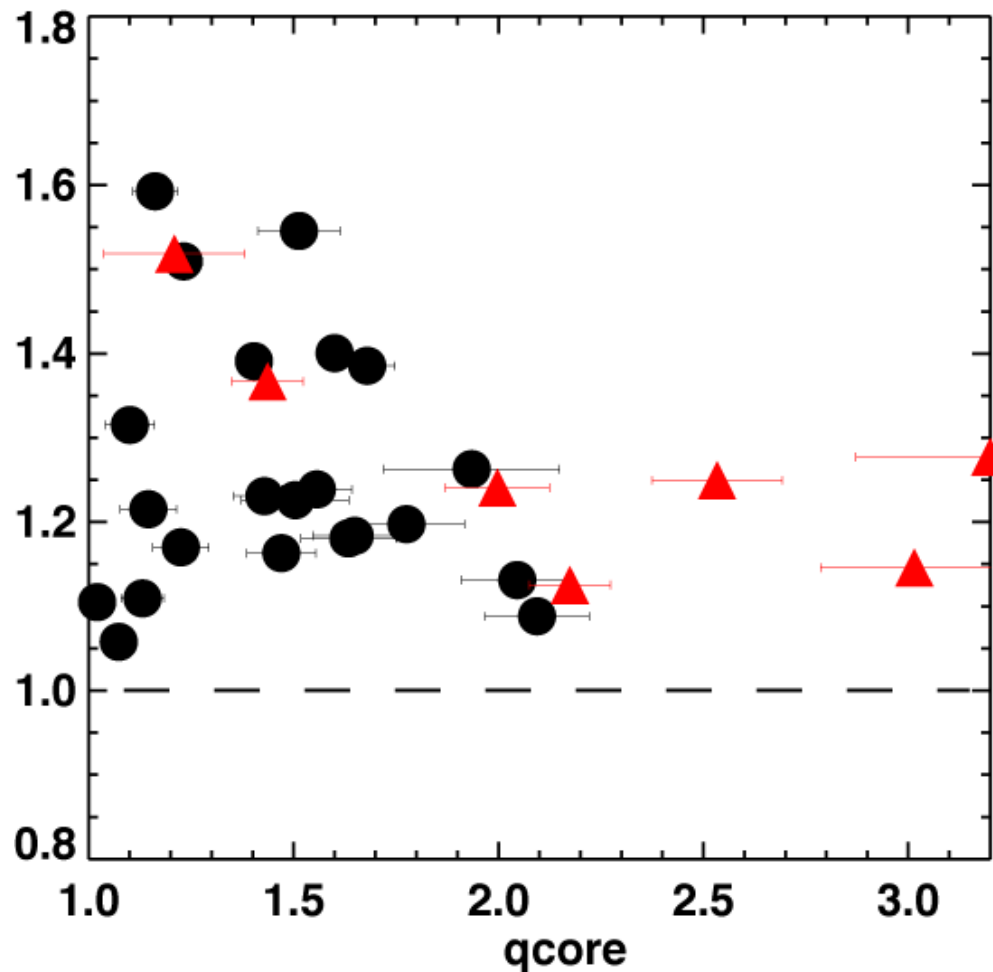


High q_{min} Plasmas With Off-Axis NBI Have $H_{98} > 1$: Typical H -Mode Level Thermal Confinement

- No off-axis beams used
 - ▲ Off-axis beams used
- “ q_{core} ” is average of q from

“Direct H98Y2”=

$$\frac{\frac{W_{thermal}}{P_{input}}}{\tau_{98Y2}}$$



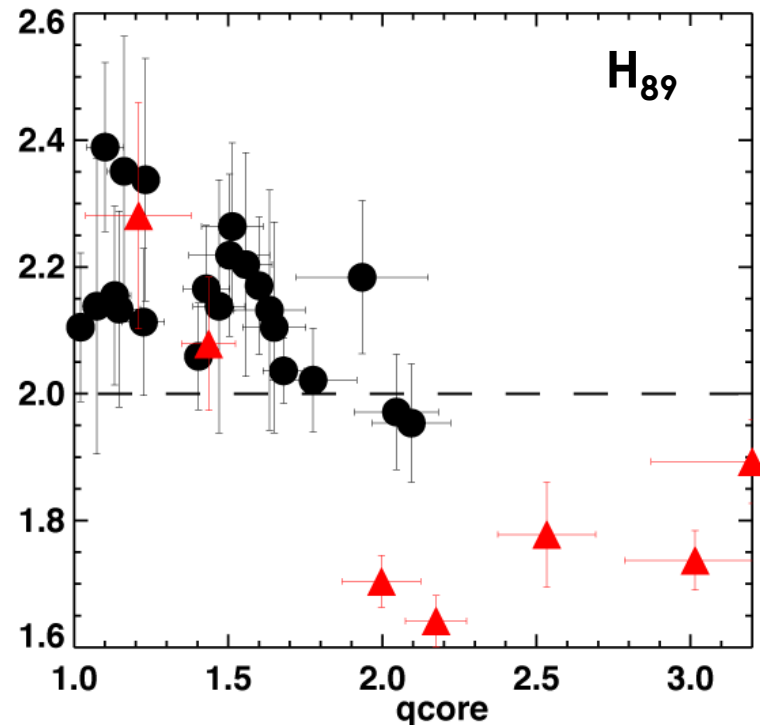
H_{98} includes only thermal stored energy

Enhanced Fast Ion Transport May Contribute to Lower H_{89} at the Highest q_{min}

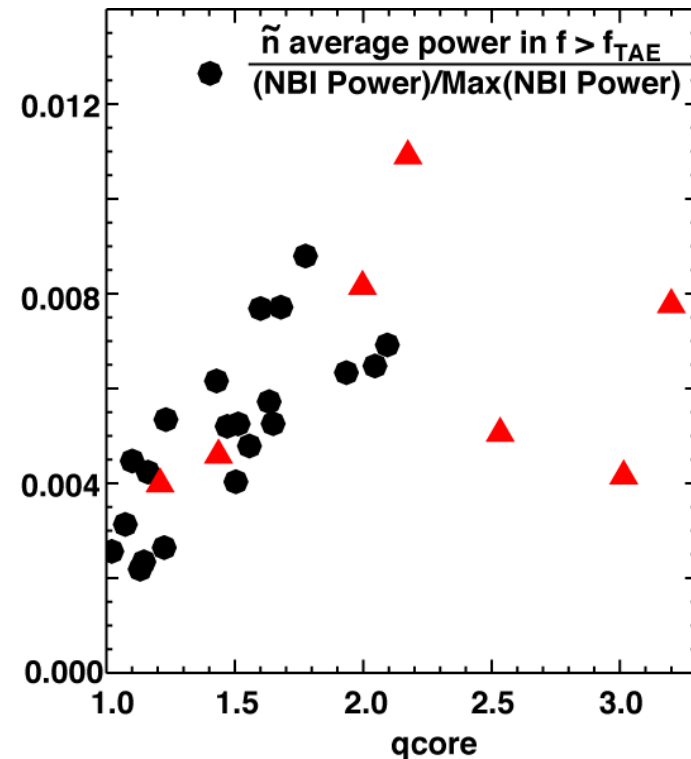
● No off-axis beams used

▲ Off-axis beams used

“ q_{core} ” is average of q from $\rho=0-0.3$

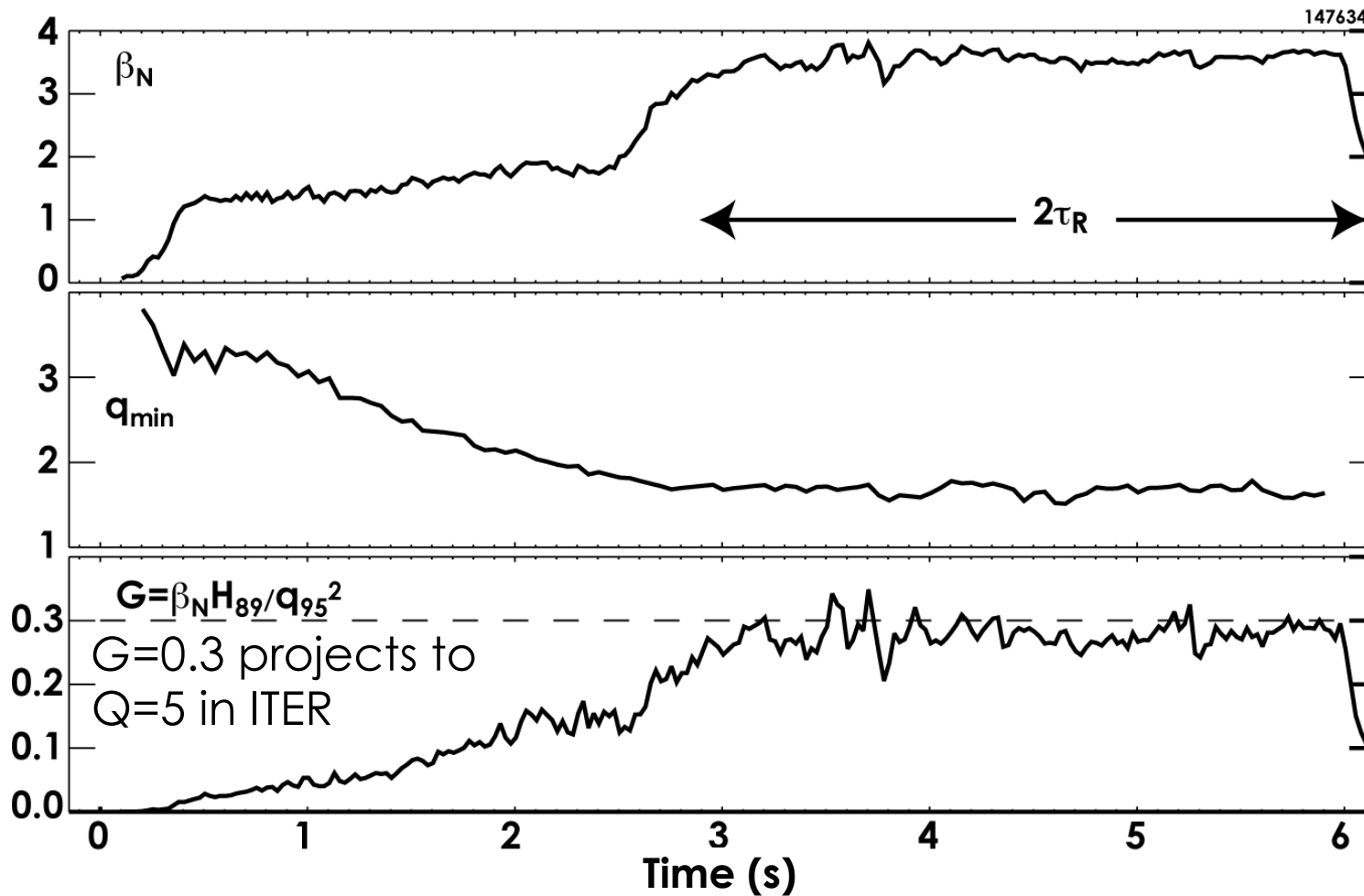


Fluctuation power in Alfvén
Eigenmode frequency range
generally increases with q_{core}



- At high q_{core} , total stored energy computed by ONETWO transport code exceeds that measured by EFIT unless anomalous fast ion transport is included

For ITER & FNSF-AT, a Relaxed High q_{min} Constraint May Still Meet the Steady State Mission Goals



- Off-axis CD maintains quasi-stationary $q_{min} \approx 1.5$ scenario with good H_{89}
- Stable to 2/1 modes for 2 current profile relaxation times
- Improves confidence equilibrium will not evolve to unstable state

At $\beta_N=3.5$, the Current Profile is Nearly Stationary Even With $\sim 25\%$ of I_p Driven Inductively

Current Drive Balance

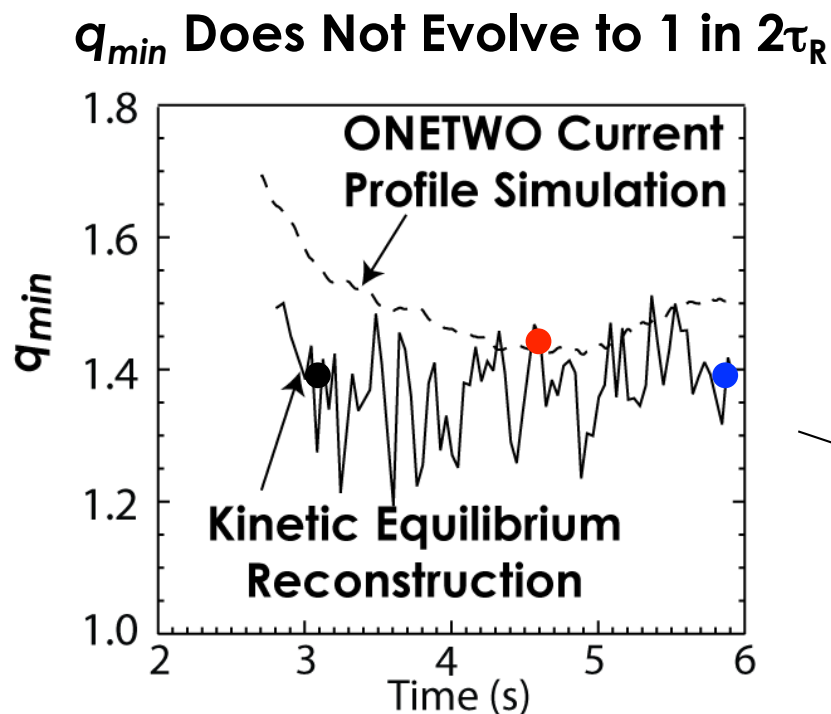
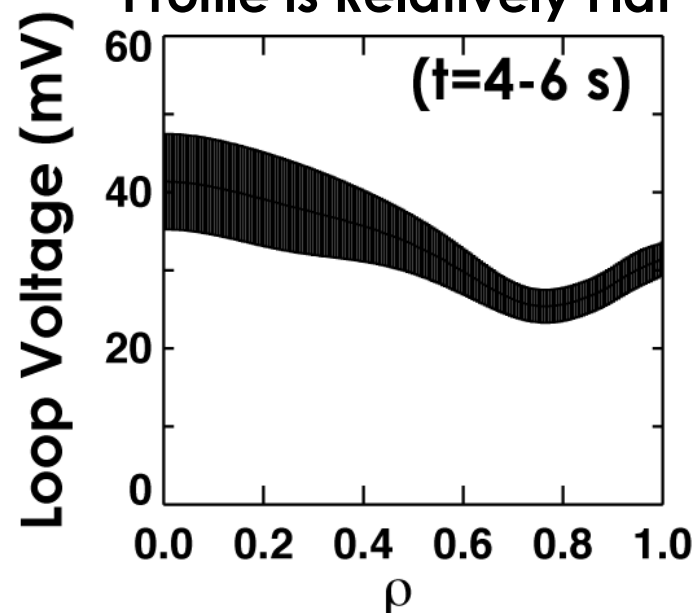
Bootstrap=50%

NBCD=20%

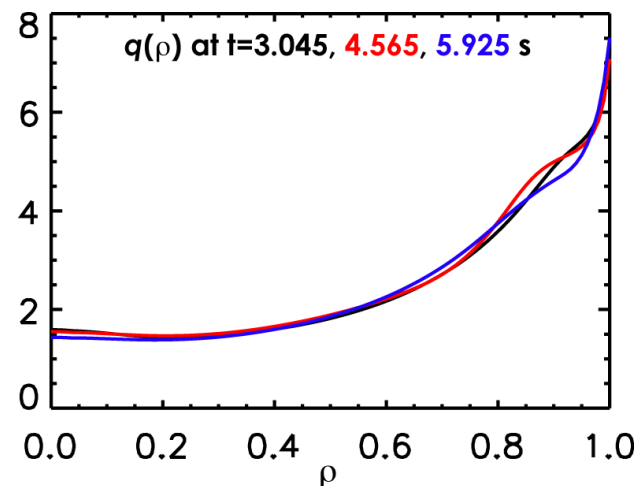
ECCD=5%

Inductive=25%

Measured Loop Voltage Profile is Relatively Flat

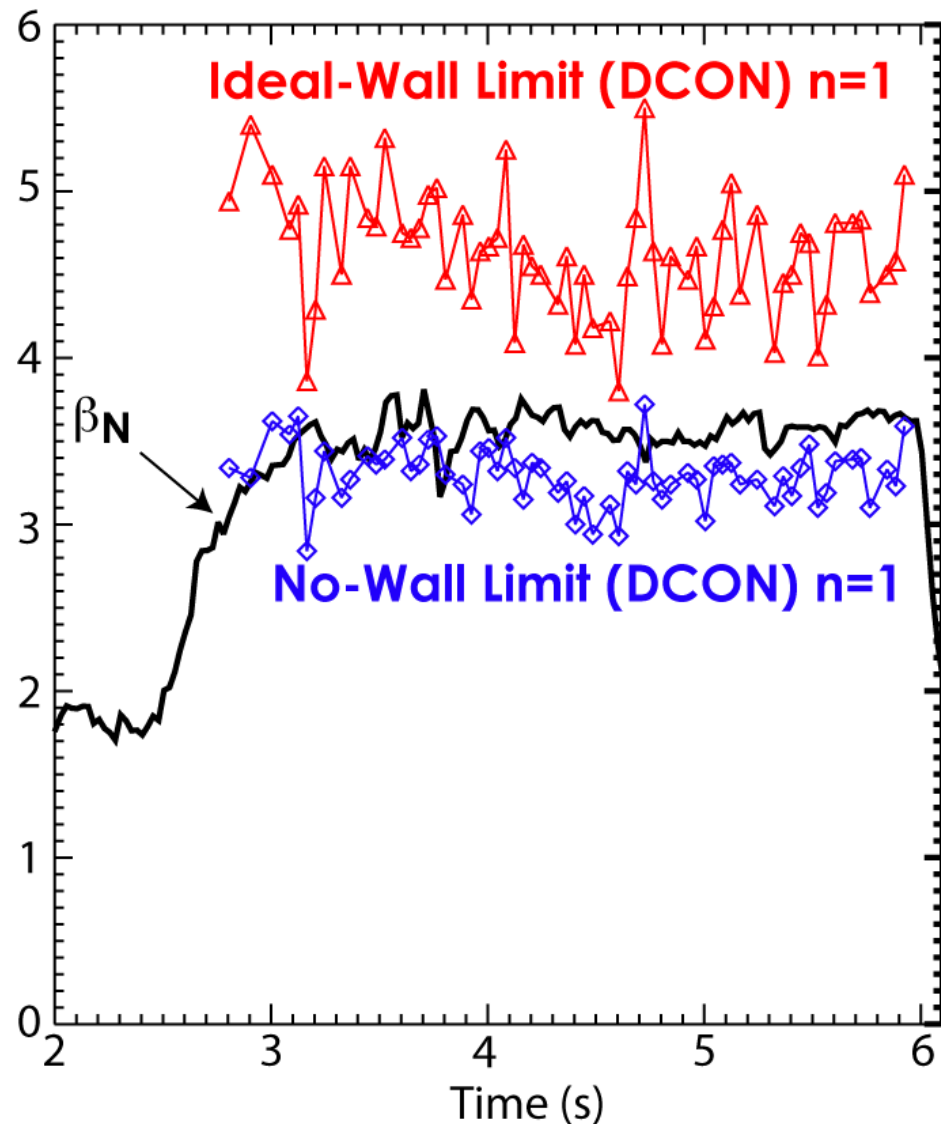


Very Little change in $q(\rho)$



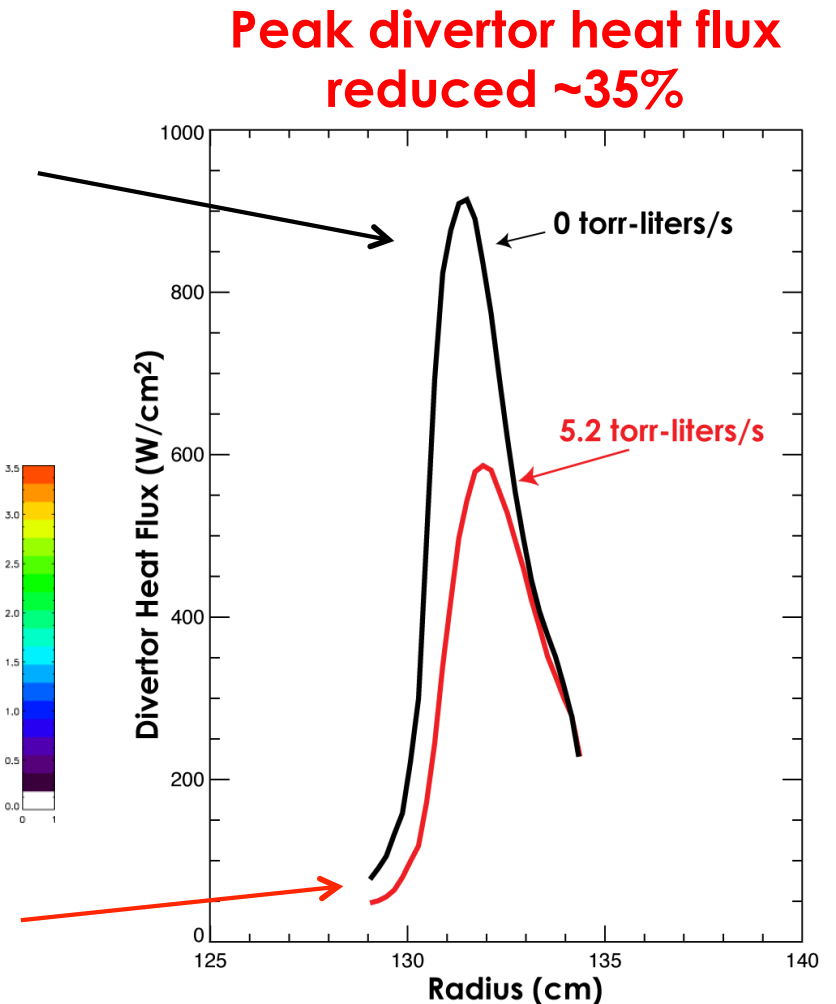
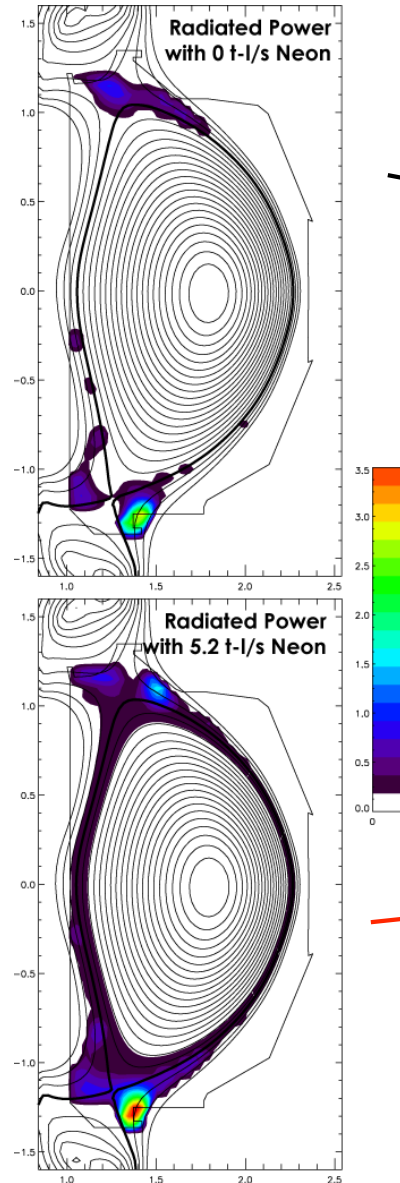
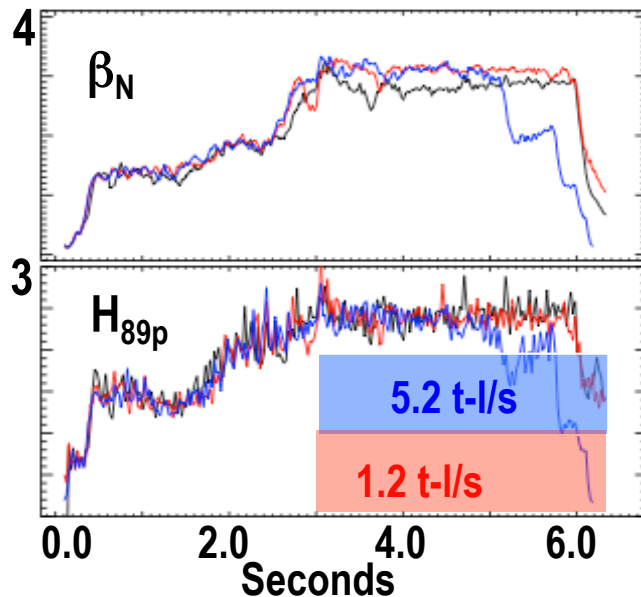
With More Power, $q_{min} \approx 1.5$ Scenario Has Margin For Improvement – Higher β_N & Full Noninductive Current Drive

- 13-30% below predicted ideal-wall limit
- Residual Ohmic current is peaked – fill in with BS, NB, & EC
- Must still avoid pressure peaking that can reduce stability



$q_{\min} \approx 1.5$ Scenario Appears Compatible With Radiating Mantle Technique for Divertor Heat Flux Reduction

- Neon injected into private flux region
- P_{RAD} doubles without significant performance degradation



(IR camera measurements)

Conclusions

- **Off-axis beams sustain more advanced profiles with better stability**
 - $q_{min} > 2$ with broad pressure: predicted ideal-wall β_N limits increased
 - ITER-sized $Q=5$ equivalent, $\sim 75\%$ noninductive scenario tested to $2\tau_R$ for tearing stability and is compatible with radiative divertor
- **Achieving high β_N with $q_{min} > 2$ will require optimizing for good τ_E**
 - Need to explore how to reduce fast ion transport in high q_{min} or compensate with higher thermal confinement, e.g. optimize q -shear
 - Future optimization will benefit from increased heating and current drive power and flexibility